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**HIGH ALTITUDE ROCKET PLUME STRUCTURE:  
EXPERIMENT AND CALCULATIONS**

**Frederick P. Boynton**

**Physical Dynamics, Incorporated**

**Prepared for:**

**Air Force Cambridge Research Laboratories  
Defense Advanced Research Projects Agency**

**June 1972**

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Contract No. F19628-72-C-0006  
Project No. 8692



Scientific Report No. 1  
June 1972

Contract Monitor: Alva T. Stair  
Optical Physics Laboratory

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## DOCUMENT CONTROL DATA - R &amp; D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified.)

1. ORIGINATING ACTIVITY (Corporate author) Physical Dynamics, Inc. P.O. Box 1069 Berkeley, California 94701		2a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	
3. REPORT TITLE HIGH ALTITUDE ROCKET PLUME STRUCTURE: EXPERIMENT AND CALCULATIONS		2b. GROUP	
4. DESCRIPTIVE NOTES (Type of report and inclusive dates) Scientific. Interim.			
5. AUTHOR(S) (First name, middle initial, last name) Frederick P. Boynton			
6. REPORT DATE June 1972	7a. TOTAL NO. OF PAGES 21	7b. NO. OF REFS 5	
8a. CONTRACT OR GRANT NO. F19628-72-C-0006 ARPA Order No. 1856		8a. ORIGINATOR'S REPORT NUMBER(S) PD-72-022 Scientific Report No. 1	
b. PROJECT, Task, Work Unit No. 8692 n/a n/a		9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) AFCRL-72-0680	
c. DoD Element 62301D			
d. DoD Subelement n/a			
10. DISTRIBUTION STATEMENT A - Approved for public release; distribution unlimited.			
11. SUPPLEMENTARY NOTES This research was supported by the Defense Advanced Research Projects Agency.		12. SPONSORING MILITARY ACTIVITY Air Force Cambridge Research Laboratories (OP) L.G. Hanscom Field Bedford, Massachusetts 01730	
13. ABSTRACT  Values of impact pressure and species number density measured in a wind tunnel experiment simulating a high-altitude rocket exhaust plume are compared with values calculated with a computer code. Considering a number of uncertainties in the absolute calibrations of the experiment, agreement is generally considered satisfactory for conditions in the mixing region between plume and free stream gases. However, in the forward part of the plume, the data suggests that free-stream gas penetrates further into the plume than the calculation predicts; the cause of this discrepancy is unknown.			

14.	KEY WORDS	LINK A		LINK B		LINK C	
		ROLE	WT	ROLE	WT	ROLE	WT
	Exhaust plumes Fluid Dynamics Mixing						

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ARPA Order No. 1856

Program Code No. 1E40

Contractor: Physical Dynamics, Inc.

Effective Date of Contract: 1 July 1972

Contract No. F19628-72-C-0006

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Contract Expiration Date: 31 December 1973

## FIGURE CAPTIONS

1. Sketch of the flow field of a rocket exhaust plume at high altitudes (continuum flow)
2. Calculated structure of the flow for VKF test condition IC5, Tunnel M, in the forward portion of the plume. Flow over body calculated with MULTITUBE; flow in the plume shock layer to junction line calculated with thin layer code; remainder of flow calculated with MULTITUBE. Shock layer is viscous, and dividing streamline is that which bounds a mass flow equal to exhaust mass flow.
3. Impact pressure along plume centerline as a function of distance from nozzle.
4. Impact pressure vs. radial distance in a plane 3 inches downstream from nozzle exit.
5. Impact pressure vs. radial distance in a plane 5 inches downstream from nozzle exit.
6. Impact pressure vs. radial distance in a plane 10 inches from nozzle exit.
7. Number densities of He and  $N_2$  vs. radial distance in a plane 3 inches downstream from nozzle exit.
8. Number densities of He and  $N_2$  vs. radial distance in a plane 5 inches downstream from nozzle exit.
9. Number densities of He and  $N_2$  vs. radial distance in a plane 10 inches downstream from nozzle exit.

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This note presents some comparisons of local values of species number density and impact pressures measured in a simulated high-altitude rocket plume<sup>1</sup> with values calculated with a computer code<sup>2</sup> which the author has used extensively over the past several years. The measurements were conducted at the Von Karman Gas Dynamics Facility (VKF) of the U.S. Air Force Arnold Engineering Development Center and included pitot-tube determinations of  $\rho u^2$  and electron-beam fluorescence measurements of the local number density  $n_i$  of plume and free-stream gases.

Interpretation of the measurements at the experimental conditions is not straightforward, since significant corrections to the raw data are required in order to determine absolute values of  $\rho u^2$  and  $n_i$ . The author has discussed the experimental results with several people connected with the experiment.\* Their consensus is that the absolute values of the data of Reference 1 may require further correction.

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\* The author particularly wishes to acknowledge discussions with Drs. L. Quinn, Air Force Rocket Propulsion Laboratory; J.D. Stewart, Aerospace Corp.; and E. A. Sutton, Aerodyne Research, Inc.

Thus, at this time only a semi-quantitative comparison with the code's predictions is possible. On the other hand, these data represent the only available experiments on local plume conditions in the range of shock layer Reynolds number characteristic of large vehicle plumes between 100 and 200 km altitude, which is the regime for which the code was originally intended. A comparison between the data and a calculation should be useful, even though some further data reduction may be needed to make the comparison completely valid.

For the comparison, we choose test condition IC5, conducted in Tunnel M at VKF. In this test a helium plume was released from a 5 psia chamber through a conical nozzle of 1.61 area ratio into a Mach 18.15 nitrogen-free stream at  $6\mu$  Hg static pressure. On Simons' map of plume regimes,<sup>3</sup> this flow field would lie slightly above the lines corresponding to merging of the barrel shock and the low-altitude boundary of the transitional regime. The computer code performs a "viscous layer" calculation in which the shocks are assumed to be thin. Between the two shocks, the equations of motion consist of the full Euler equations with viscous terms resembling those in the boundary layer equations. (See Reference 2 for a complete description.) The mixing zone between plume and free-stream gas need not be thin with respect to the shock layer as a whole. We should therefore expect that this case

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\* A comprehensive review of the data is currently being conducted by Aerodyne Research, Inc., and it is hoped that either reliable values or reliable error estimates will be available within the next year.

should provide a stringent test of the calculation's ability to describe conditions in the mixing region between the plume and free stream.

The conditions of the experiment and calculation are given in Table I. For the calculation it was assumed that

TABLE I

Exhaust and Free Stream Test Conditions

	<u>Exhaust Gas</u>	<u>Free Stream</u>
$P_O$	258 mm H <sub>g</sub>	
$T_O$	770°K	2900°K
$P$	28.1 mm Hg	6.00 Hg
$T$	317°K	45.0°K
$u$	$2.17 \times 10^5$ cm/sec	$2.49 \times 10^5$ cm/sec
$M$	2.07	18.15
gas	He	N <sub>2</sub>
$\gamma$	1.667	1.4

all mixing was steady and laminar, that the viscosities of  $N_2$  and He could be adequately represented as power-law functions of temperature, and that Prandtl and Schmidt numbers were constant. The experimental setup includes a forebody needed to house the nozzle; this forebody was a core-cylinder with a chamfered boat-tail. The inviscid flow over this forebody was calculated and included in the description of the free stream. Any viscous effects due to boundary layer formation or separation are not included in the calculation. Except for the nose region of the plume, where the air shock is detached, the calculations were performed with the MULTITUBE code. In the nose region, a recently developed thin layer code<sup>4</sup> was employed. Partly because of the configuration of the nose region of this plume, this calculation's description of the nose region is poor, and it should be regarded more as a means of providing reasonable initial conditions to the wholly supersonic part of the plume than as a realistic description of the nose region. That the initial conditions are in fact adequate is evidenced by the behavior of the supersonic calculations, which exhibit only mild pressure oscillations in the first centimeter or two downstream of the transition between the two methods of calculation. The results of the calculation in the forward region of the plume, including the forebody flow, are shown in Figure 2.

Impact pressures as a function of axial distance from the nozzle are shown in Figure 3. The measured values lie

close to, but slightly below, the computed values until about 15 cm downstream, at which point the measured values rise above the computed values and actually increase beyond 35 cm downstream. This most likely reflects the upstream influence of the Mach disc, which is expected to be very diffuse in this plume.

Impact pressures as a function of radial distance from the centerline are shown in Figures 4-6 at distances of 3, 5, and 10 inches (7.6, 12.7, and 25.4 cm) downstream. The major apparent qualitative difference between calculation and experiment is the thickness of the experimental shocks (expected on the basis of Simons' regime map). Absolute values of the measured and calculated  $\rho u^2$  agree rather well in the internal region of the shock layer and somewhat less well elsewhere. (Since further correction to the measurements may be needed, one cannot make too much of any absolute comparisons at present.) It does appear from the measurements that the jet shock is quite thick. The predicted peak in the impact pressure profiles on the inner side of the plume shock layer (a result of competition between an outward pressure gradient due to centrifugal forces and an outward temperature gradient due to heat conduction from the shocked  $N_2$ ) is only found at the three-inch station. Outside of these thick shocks, the agreement of calculation and experiment is quite satisfactory.

He and  $N_2$  molecule number densities determined from electron-beam fluorescence measurements are compared with the calculated values in Figures 7 - 10. One should be aware that at the time these measurements were made the electron-beam technique was still under development at VKF, and that many questions remain concerning absolute calibrations in He- $N_2$  mixtures, including beam spread, secondary electron effects, and quenching of excited states. Where the flow is mostly  $N_2$ , a good check is afforded by comparison with the known free-stream conditions. The values of  $n_{He}$  quoted in Reference 1 are consistently 40 - 60% larger than those determined from the calculation. If one accepts the quoted nozzle properties (from which one can calculate the number flow of He atoms), then either the calculated velocities in the He plume are very badly wrong, a circumstance which would do violence to a number of long-accepted concepts in gas dynamics, or there is a sizeable correction required in the reported absolute He number densities.

The qualitative behavior of the calculated and measured values of  $n_{He}$  is substantially the same except in the region of the jet shock. In fact, simply reducing the reported values of  $n_{He}$  by 40% brings them into rather satisfactory quantitative agreement with the calculation. Conservation of helium molecules at velocities approaching the limiting velocity (2.5 to 2.8 km/sec) requires a correction factor of this order, though of course it may be different in different re-

gions depending upon density, temperature, and composition.

The calculated and measured values of  $n_{N_2}$ , excepting the region of the free-stream shock, are in very satisfactory agreement at the 10-inch station (Figure 9). However, at locations further upstream the measurements show considerably greater penetration of  $N_2$  molecules at the inner edge of the jet shock. This anomalously high diffusion is also evident in the results of test IC2 of this series and in several tests conducted in the 10-V tunnel.<sup>5</sup> The discrepancy between the observed and predicted diffusion of  $N_2$  into the jet is disturbing, since it suggests that temperature profiles could also be broader than calculated. If this is the case, estimates of emission from the forward part of the plume may be significantly in error.

Several possible reasons for the discrepancy have been examined, and none seems to supply a satisfactory explanation of it. It is difficult to ascribe it to some rarefied flow phenomenon, since an average  $N_2$  molecule entering the plume upstream from this region suffers 10 to 20 collisions before getting across the shock layer. Thus the proper description of molecular motion is in terms of diffusion rather than molecular penetration, and this description is embodied in our calculation. It is possible that the forebody introduces some additional mixing into the forward part of the plume. We cannot assess this effect with available codes. Discuss-

sions with people responsible for the tests indicate that great care was taken to align the electron beam in the Tunnel M test series, and it is doubtful that measurement errors arise from that source. There are other possible errors, such as those due to beam spread, secondary electron effects, and movement of the molecules before emission. Assessment of these effects is currently under way elsewhere, and we should properly reserve comment until this reinterpretation of the data is complete. However, we note that there is a difference in radial location of the measured maxima in  $\rho u^2$  and  $n_1$  for the 3-inch and 5-inch stations, while we should expect these to be coincident.

In summary, the available data provide only a semi-quantitative test of the computational procedure because of questions regarding calibration. Within these limits, the agreement of experiment and calculation within most of the mixing region between plume and free stream is acceptable. The apparent deep penetration of  $N_2$  molecules into the plume near the nose is unexplained. Unfortunately, no comparison can currently be made with local temperatures, which are of considerable importance to radiation calculations.

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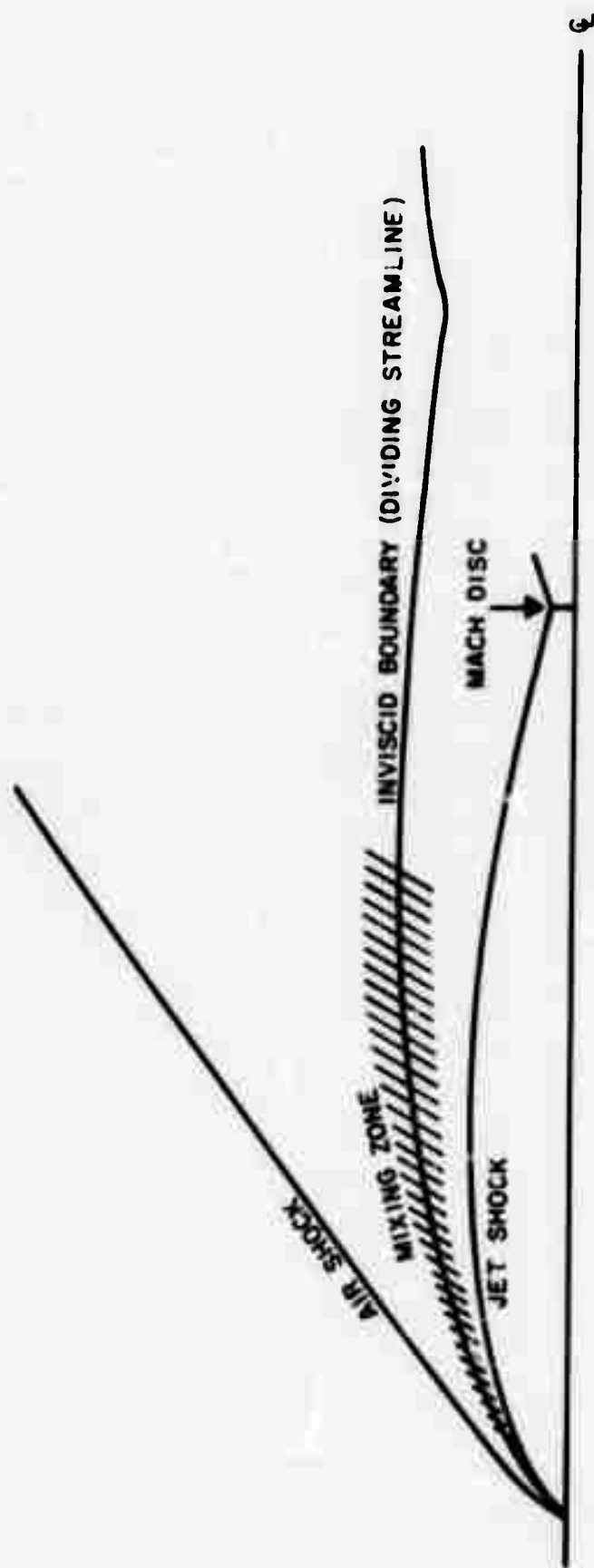
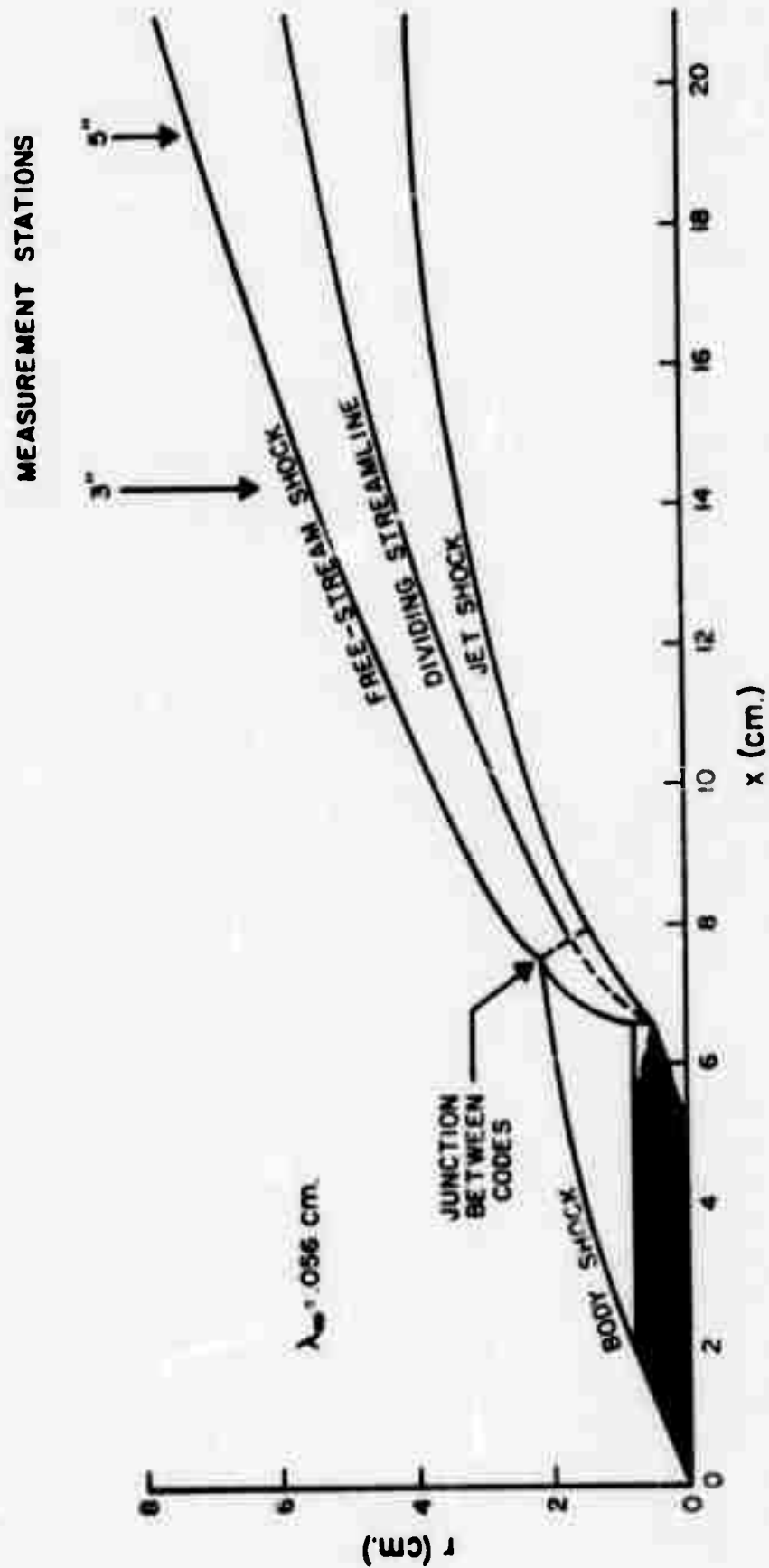


FIGURE 1. SKETCH OF THE FLOW FIELD OF A ROCKET EXHAUST  
PLUME AT HIGH ALTITUDES (CONTINUUM FLOW)

FIGURE 2. CALCULATED STRUCTURE OF THE FLOW FOR VKF TEST CONDITION IC5, TUNNEL II, IN THE FORWARD PORTION OF THE PLUME. FLOW OVER BODY CALCULATED WITH MULTITUDE; FLOW IN THE PLUME SHOCK LAYER TO JUNCTION LINE CALCULATED WITH THIN LAYER CODE; REMAINDER OF FLOW CALCULATED WITH MULTITUDE. SHOCK LAYER IS VISCOUS, AND DIVIDING STREAMLINE IS THAT WHICH BOUNDS A MASS FLOW EQUAL TO EXHAUST MASS FLOW.



— CALCULATED  
x EXPERIMENTAL

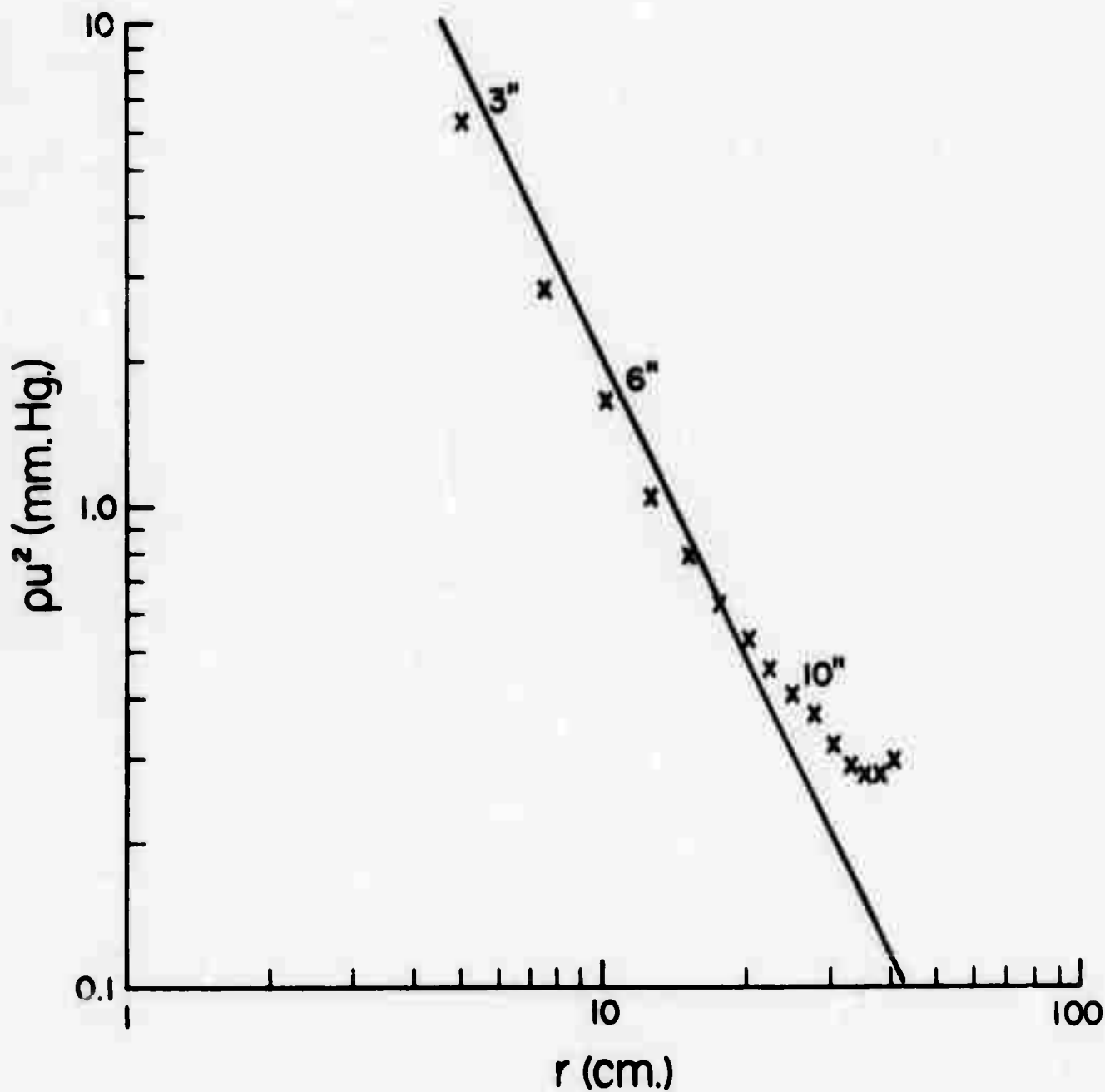


FIGURE 3. IMPACT PRESSURE ALONG PLUME CENTERLINE AS A FUNCTION OF DISTANCE FROM NOZZLE

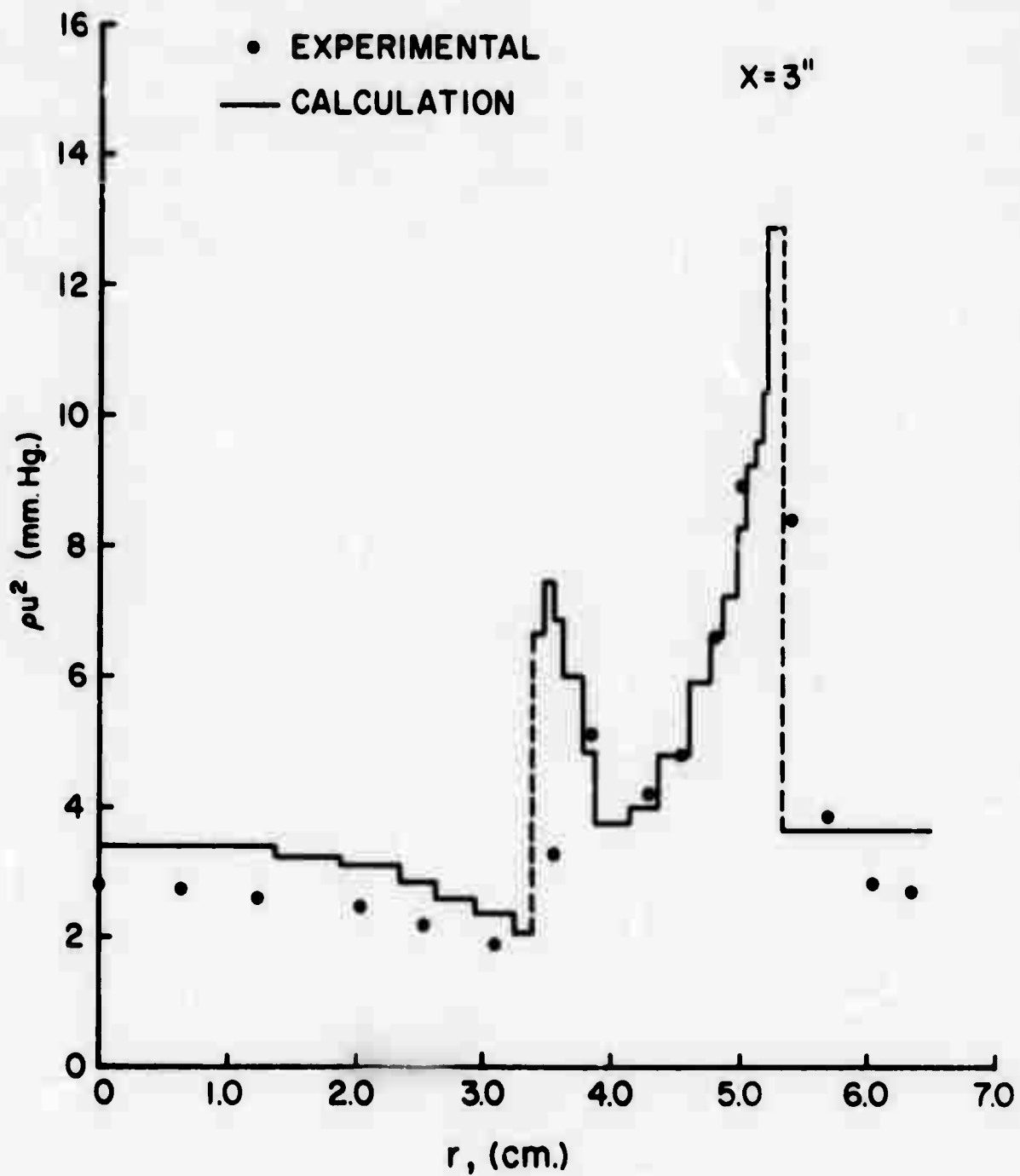
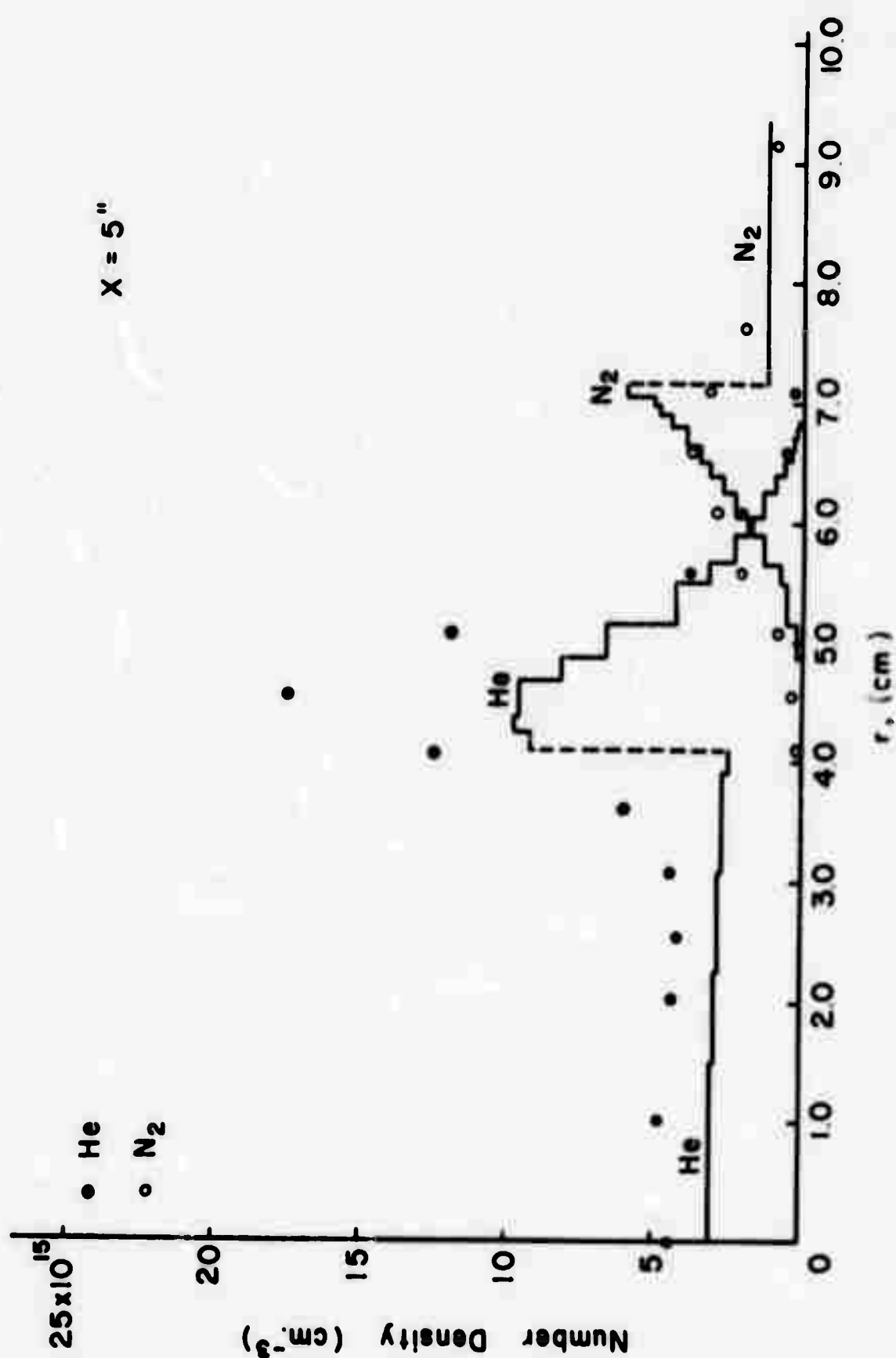


FIGURE 4. IMPACT PRESSURE VS. RADIAL DISTANCE IN A PLANE 3 INCHES DOWNSTREAM FROM NOZZLE EXIT

FIGURE 5. IMPACT PRESSURE VS. RADIAL DISTANCE IN A PLANE  
5 INCHES DOWNSTREAM FROM NOZZLE EXIT



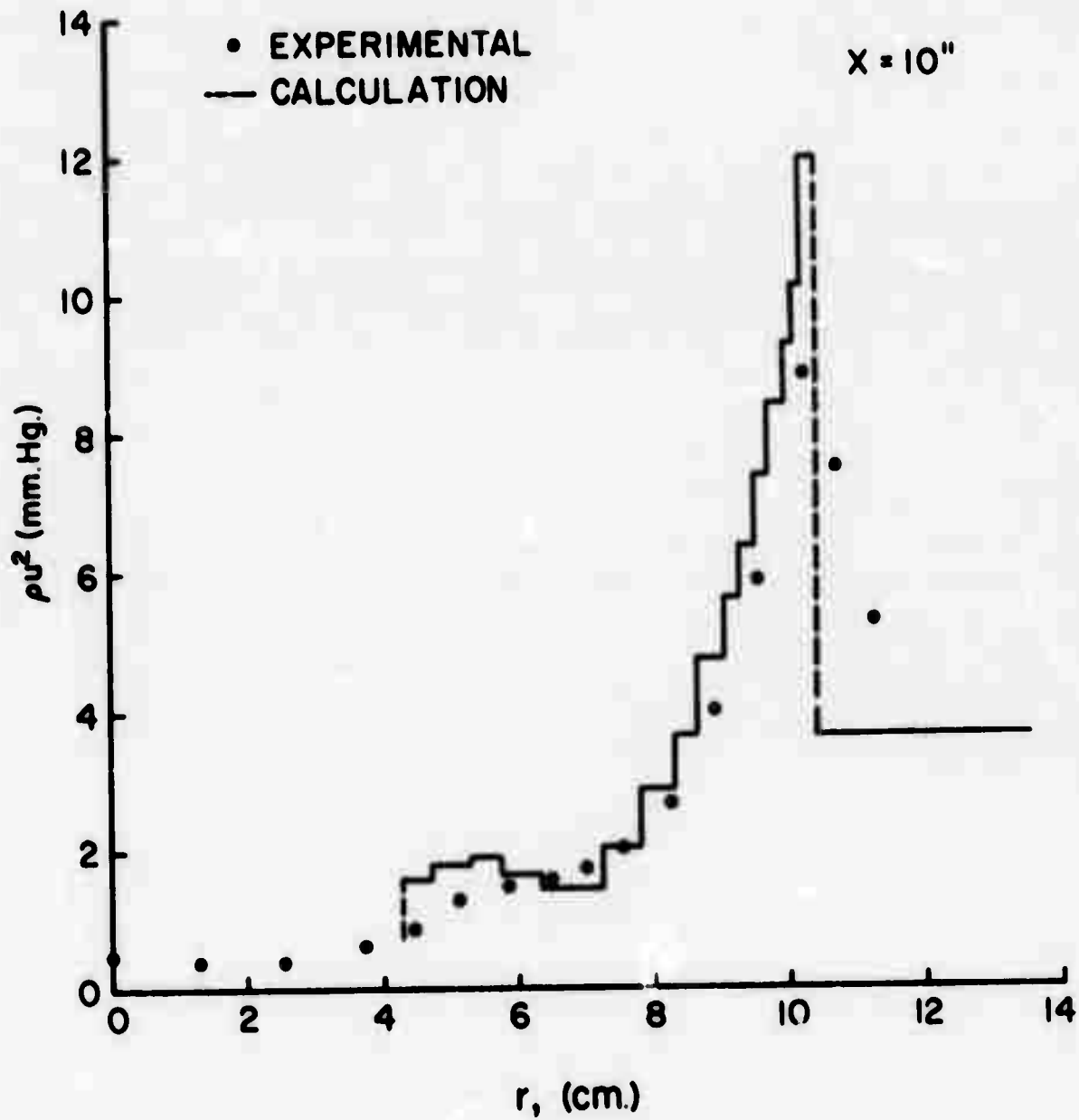


FIGURE 6. IMPACT PRESSURE VS. RADIAL DISTANCE IN A PLANE 10 INCHES FROM NOZZLE EXIT

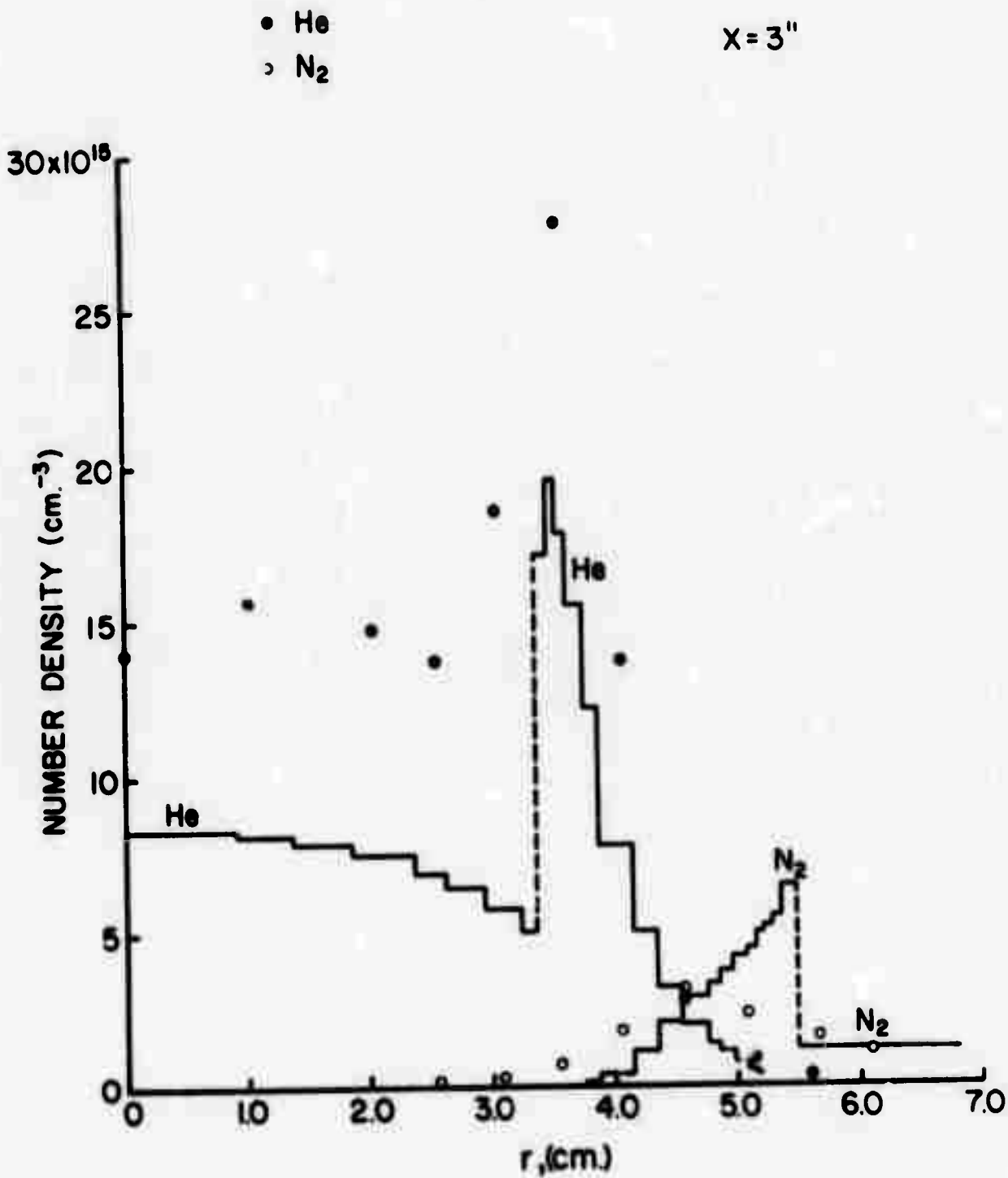
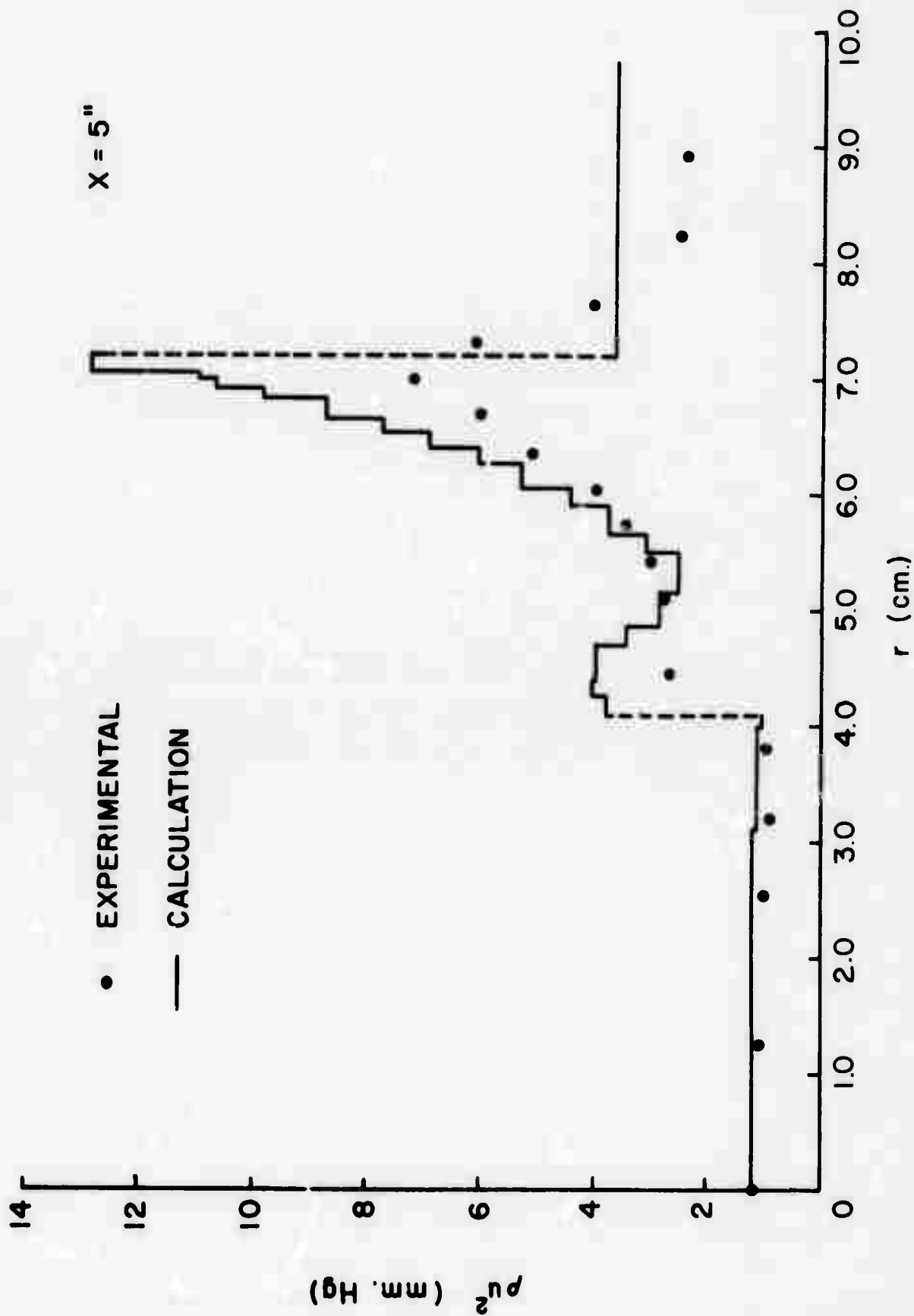


FIGURE 7. NUMBER DENSITIES OF HE AND N<sub>2</sub> VS. RADIAL DISTANCE IN A PLANE 3 INCHES DOWNSTREAM FROM NOZZLE EXIT

FIGURE 8. NUMBER DENSITIES OF HE AND  $H_2$  VS. RADIAL DISTANCE IN A PLANE 5 INCHES DOWNSTREAM FROM NOZZLE EXIT



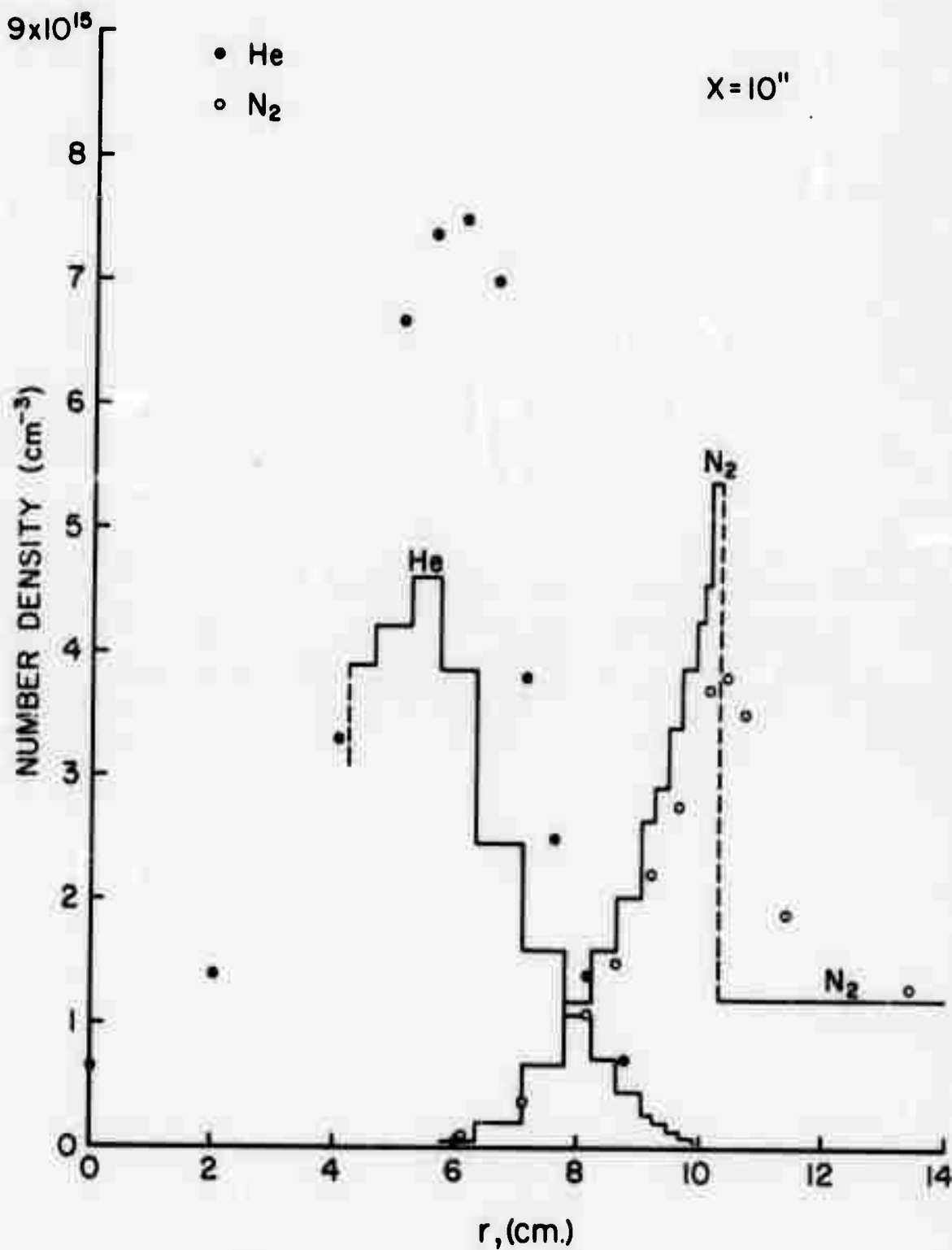


FIGURE 9. NUMBER DENSITIES OF HE AND N<sub>2</sub> vs. RADIAL DISTANCE IN A PLANE 10 INCHES DOWNSTREAM FROM NOZZLE EXIT